Automatic Structural Optimization of Engine Components Using HCF and TMF Failure Analysis and Optimization Models

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***Abstract*- Modern combustion methods and the constant wish for an increase in the specific performance results in high thermal and mechanical loads in modern combustion engines. In order to shorten the development time, an interactive, simultaneous execution of design (CAD) and calculation activities (CAE) is necessary. In this the product must be looked at in detail and be optimized in various disciplines and in a harmonized way of procedure to the development progress. In the initial proactive phase the efficiency of virtual CAE-methods is high and quickly decreases in the second half of the development, which shows strongly reactive features. Therefore a combined HCF (*High-Cycle-Fatigue*) Failure Analysis and Optimization and TMF (*Thermo-Mechanical-Fatigue*) Failure Analysis and Optimization model is discussed in this paper for the reduction in the analysis time.**

***Index Terms*- Exhaust manifold, HCF, TMF, FEM, FEV**

I. INTRODUCTION

Exhaust Manifold is a simple pipe, which carries the burned gases. In a multi cylinder engine, individual pipes collect the combustion products from various cylinders and lead to a single outlet pipe. Exhaust manifold is subjected to thermal boundary conditions (loading).

A. Basic functions of the exhaust manifold

1. It is a pipe which carries away the burned gases out of the engine cylinders
2. It insulates the exhaust gases from the surrounding so that catalytic converter functions well; the functioning of the catalytic converter depends on the prevailing temperature in the manifold.
3. It conducts away sufficient amount of heat so that inner surface temperature of the exhaust manifold is less than the melting point of the exhaust manifold.

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II. SHAPE OPTIMIZATION

Shape optimization can be differentiated in parametric and parameter-free methods. In a parametric optimization design parameters such as length and radii are modified. In the ideal case this already takes place in the CAD system with automatic secondary FEM (Finite Element Method) calculation; in practice this method is often impeded by interface problems. Apart from that, the space for the possible solution is considerably restricted, owing to the limited number of design variables. Due to which the solution found, in comparison to the possible solution in the complete solution space shows only sub-optimal properties. In highly stressed components like the curvature resistant surfaces this has turned out to be of advantage as regards to stress distribution. Hence a simple parameterization with radii of curvature resistance can only be achieved with difficulty.

III. HCF (HIGH-CYCLE-FATIGUE) FAILURE ANALYSIS AND OPTIMIZATION FOR GLOBAL MODEL

The high-cycle-fatigue failure mechanism is caused through a constant and critical combination of mean and amplitude stresses. Here the local stress gradients, the orientation of stresses (tensile/compressive) and various material-specific parameters (surface, porosity, etc.) are of great importance. The lower stress limit of the alternating load is mainly produced by the load from residual stresses (casting processes, heat treatment, machining), assembly (bolting loads and press fits) and temperature (combustion). The maximum stress the high-frequency periodic load, due to gas pressure, is superimposed. By the superimposition of residual stresses and cyclic loads, the fatigue life of the component may be considerably reduced. Critical areas of modern cylinder heads are typically the transition radii of the ports (intake/outlet) to the flame deck or oil deck, where erratic differences in stiffness are often found in the structure. For the following investigations the internal stresses were neglected. The implementation of the fatigue analysis in the optimization loop offers essential advantages in complex structures, though places of highest mean stress are not always the places of greatest damage.

IV.TMF (THERMO-MECHANICAL-FATIGUE) FAILURE ANALYSIS AND OPTIMIZATION

Apart from the cylinder head structure the shape optimization is also applicable at all further highly loaded structures in the combustion engine like the exhaust manifold. In this component the damage is not caused by alternating ignition pressures, but by thermal load alternations. Already after the first load cycle, plastic deformations can often be seen in some areas of the exhaust

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manifold. The high material temperatures due to the limited possibility of thermal expansion, owing to different material parameters and the screwed connection, lead to high compressive stresses, which locally exceed the yield point of the hot solid material.

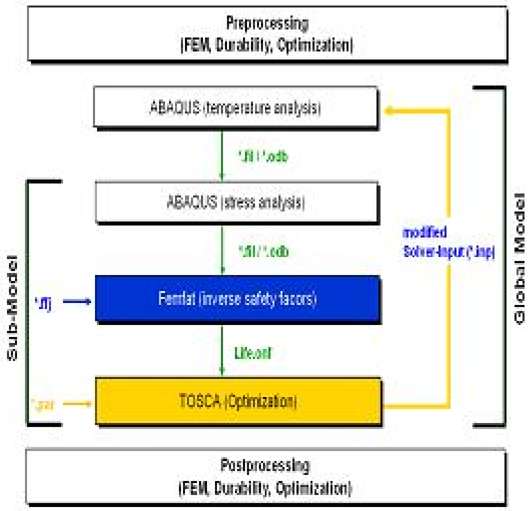

Figure 1. HCF (High-Cycle-Fatigue) Failure Analysis and Optimization for Global Model

In these plasticized zones the compressive stresses, after cooling down of the engine, change into local tensile stresses, which in the unfavorable case can locally exceed the tensile yield point. In such a case cyclically repeated plastic strain amplitude occurs, which is the basis for the thermo-mechanical failure mechanism. Special importance in this connection is also given to the contact formulations between cylinder head, gasket and exhaust manifold, as well as the non-linear behavior of the exhaust manifold gasket. Compared to the fatigue life characteristics from experiments, the service life of the component can be determined via strain or energy approaches. As the optimality criteria is also applied to moderately non-linear analyses like plasticity or hyper-elasticity, also certain non-linear analyses can be used in shape optimization. As regards to the plasticity, a homogenization of the elastic and plastic stain energy is strived for, by which the maximum strain energy and with that the maximum plastic strain is reduced. Therefore, the optimization quantity, in the first formulation, is not a damage that is looked at, but plastic strain amplitude. From the results of the test bench runs, a good correlation of crack starting points to areas of high plastic strain amplitude can be derived in comparison to the analyses. An extension of the TMF-based damage calculation and integration into the optimization process is in principle possible. The determination of the damage through TMF is comparable to the already described analyses at the cylinder head. In the thermal analysis the influence of radiation is taken into consideration, besides comparable boundary conditions as used for the cylinder head analysis. Averaged heat transfer coefficients and gas temperatures are determined as in stationary CFD analyses.

A. The mechanical loads consist of the following:

- Pre-stresses from bolt loads
- Thermo-mechanical stresses caused by various thermal expnsion coefficients of cylinder head and exhaust manifold as well as other mounting parts.
- Thermo-mechanic stresses through temperature gradients in the materials of the component parts

Residual stresses and dynamic stresses can be neglected for the determination of the TMF-failure. The optimization of the exhaust manifold and the analysis takes place according to the "closed loop" method, (i.e.) by integration of the thermal analysis. The gas-side boundary conditions are kept constant, as in the first approximation the local modifications at the geometry do not have any significant effects on the gas flow. As an exact representation of the temperature distribution for the evaluation of TMF is important, measurement based on thermo-scan methods or by means of thermo-color can be carried out in the preliminary stages of the analyses.

All internal and external surfaces of the ports were selected as design area. The geometry of the flange surfaces and bolt bores were fixed. During the mechanical analysis the following load history is passed through:

1. Assembly
2. Thermal load
3. Cooling down to room temperature
4. Thermal load
5. Cooling down to room temperature

The total analysis time is at approx. 2.5 hours, with the thermal and mechanical analysis representing almost 100 % of the work. In total 30 optimization loops were carried out. The release of such a large design area is a challenge for the optimization algorithm. Local modifications at one area can change the total stiffness of the exhaust manifold and consequently influence the results of further areas.

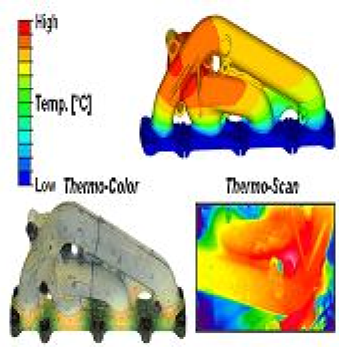

Figure 2. Temperature distribution measurement based on thermo-scan method

This is very well recognized in the internal area of the flange to the turbocharger. Here after 9 cycles a plastic strain reduced by 53 % is achieved. After 13 cycles, the local result aggravates to –35 % and the optimal result is achieved after 15 cycles.

V. CONCLUSION

- The possibility of carrying out a shape optimization on an already existing FE-model, by taking non-linear behavior and specific service life simulation into consideration, has turned to be an enormous relief and noticeable improvement in the development process.

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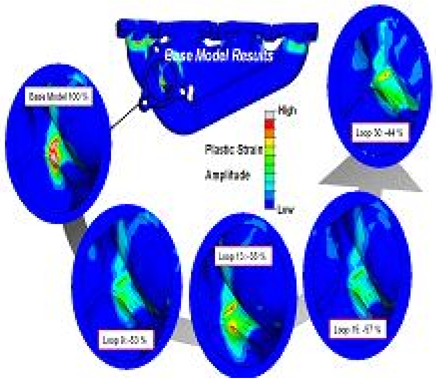

Figure 3. Thermal and Mechanical analysis

- The geometry modifications achieved are partly very minor, but have a very strong influence on the service life and on the quality of the component parts.
- Material saving at equal service life and by using the same materials, a significant extension in the fatigue life is achieved.
- The complex task of the optimization of a large area with plastic strain amplitudes has given a very good result with a reduction in the critical values of 50 % and more.
- The first steps for the implementation of the FEV Software into the optimization cycle for TMF driven problems is achieved.

VI. REFERENCES

[1] Deger.Y., “Simulation of Thermo mechanical Load Cases”, *Sulzer Technical Review*, Vol.3, 2003.

[2] Simperl.B., Schöck.J. Deger.Y, “Thermal Deformation and Stresses in an Exhaust Manifold”, *Technical Report Nr. TB03_0123, Sulzer Innotec*, Oct. 2003, (not public).

[3] ABAQUS User’s Manual, Version 6.7

[4] S.S. Manson;”Behaviour of materials under conditions of thermal stresses”, *Technical report, TN 2933, N.A.C.A*, 1953

[5] N. Mamiya; et al. “Thermal fatigue life of exhaust manifolds predicted by simulation”, *SAE Paper no. 01-0854*, 2002

[6] P.O. Santacreu; et al. “Study of thermal fatigue of stainless steels and its application to the life prediction of automotive exhaust line components”, *Congress Thermal Stress’99, Cracow, Poland, Skrzypek and R.B.HetnarskiEds*., pp.245,1999.

[7] Sandeep Patel, Nickel Daniel, “Structural Optimization of Engine Components Using ABAQUS and TOSCA”, *Project report*,2007

DOI: 01.IJPIE.01.01.13